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PROJECT DEEP STEAM:
THIRD MEETING OF THE TECHNICAL ADVISORY PANEL
BAKERSFIELD, CA, MARCH 1980

R. L. FOX, D. R. JOHNSON, A. B. DONALDSON,
A. J. MULAC, AND D. A. KRUEGER

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MATERIALS STUDIES

D. R. Johnson
Sandia Laboratories, Albuquerque, NM

I. Materials Compatibility Studies

Testing of materials in environments comparable to that encountered in fire floods has been carried out using a gas pressure of 1 bar. The composition of the test gas was chosen to produce fugacities representative of 100 bar fire flood conditions. The simulant gas fugacities are given in Table I. The performance of a selection of alloys in the simulated fire flood environment is presented in Table II.

The sealing element from the Foster-Miller extruded metal packer (see page 17) has been tested by exposure to 300°C moist hydrogen sulfide and hydrogen atmosphere for five days. The seal ring was made of aluminum with a relatively uniform silver plating. There was appreciable attack of the silver; however, the aluminum was unaffected.

Table I. 1-Bar Simulant Gas to Produce Fugacities
Existing at 100 Bars

Temperature	Gas Composition			Fugacities	
	H_2O	H_2	H_2S	$\log f_{S_2}$	$\log f_{O_2}$
250°C	97.92%	0.22%	1.86%	-10.9	-38.2
300°C	99.50	0.32	0.17	-11.8	034.3

II. Elastomeric Material for DEEP STEAM Applications

Elastomeric materials which are known to exhibit comparatively smaller degradation under high temperature conditions have been studied in a sour gas. The performance of a selection of elastomers is contained in Table III. The greatest thermochemical stability was provided by Kalrez with EPDM, Aflas and Viton having respectively poorer performance. The predominate failure mechanisms were cross-linking in EPDM and Alfes at 260°C, with reversion dominate at 370°C. The complete degradation of all elastomers tested occurred at 371°C.

Table II. Corrosion Behavior of Some Alloys at 300°C in a Simulated Fire-Flooding Environment

Alloy	Composition*				Exposure Time, Days	Weight Gain mg/cm ²	Remarks
	Fe	Cr	Ni	Other			
Mild Steel	Bal.	-	-	0.2C	30	3.54×10^{-1}	Dark film, severe pitting.
410 Stainless	Bal.	12	-	-	34	2.52×10^{-2}	Severely pitted (not as badly as mild steel).
430 Stainless	Bal.	17	-	0.12C	31	3.45×10^{-2}	Extensive pitting.
440A Stainless	Bal.	17	-	0.7C	31	3.76×10^{-2}	General corrosion, extensive pitting.
446 Stainless	Bal.	26	-	-	31	2.74×10^{-2}	Generally bright shiny surface, localized tarnish, some pit formation.
26-1	Bal.	26	-	1 Mo	34	2.52×10^{-2}	Bright, shiny surface, 1 pit.
304 Stainless	Bal.	18	8	-	31	5.93×10^{-2}	Extensive pitting.
309 Stainless	Bal.	23	14	-	34	2.58×10^{-2}	Bright, shiny surface, no apparent attack.
310 Stainless	Bal.	25	20	-	34	1.94×10^{-2}	Shiny surface, 3 pits.
316 Stainless	Bal.	18	10	2 Mo	31	1.09×10^{-2}	Light tarnish, some pit formation.

* Nominal compositions. All the stainless steels contain approximately 1% silicon and 1% manganese.

Table III. Effect of Steam and Sour Gas* on the Dynamic Shear Moduli of Elastomers

	<u>Temp (°C)</u>	<u>G' Before</u>	<u>G' After</u>	<u>% Change</u>
Kalrez	260	8005	8006	0
	300	8416	6025	-18
	371	----- Sample Powdered -----		
EPDM	260	4207	5065	+20
	300	4511	3184	-29
	371	----- Sample Powdered -----		
Viton (Peroxide Cured)	260	2053	24281	+1183
	300	--	--	--
	371	--	--	--
Aflas	260	11754	17536	+19
	300	17837	8882	-50
	371	----- Sample Powdered -----		

* Composition (mole %): 1.3 sour gas, 15% steam, balance N₂.

III. Hard Coatings

The application of hard coatings for improving erosion resistance in critical components in oil field operation is under investigation. A failed gate valve, used in a recovery project using the Vapotherm process, has been examined for treatment with TiB₂. Analysis of the technique for depositing TiB₂ on the valve has been carried out. The field testing of a hard coated valve was not possible due to a piping modification which eliminated the use of sliding valves.

INSULATION/PACKER SIMULATION TEST

P. Taylor and B. Traynor
General Electric Co., Tacoma, WA

The objective of the insulation/packer simulation test program is to perform a feasibility evaluation regarding the modification of the delivery system of steam to improve the thermal efficiency of oil well completions. The test involves:

1. Comparison, relative to bare tubing, of the thermal efficiency of various insulated steam injection tubulars;
2. Evaluation of effects of life cycling;
3. Evaluation of various high temperature packers; and
4. Correlation of computer modeling and test data.

The test program required the construction of a facility with the following capabilities:

1. Ability to test various tubulars and packers in 7" casing.
2. Test article lengths up to 60' accommodated.
3. High pressure and high temperature steam capability.
4. Ability to vary soil temperature.
5. Capability to change soil characteristics.
6. Complete monitoring of data.

A 70-foot above-ground test tower was developed to meet these testing requirements. The test tower, located in Tacoma, WA, is shown in Figure 1. A section of the interior of the tower is given in Figure 2. The data which will be monitored during test operation is stated in Table IV. The schedule for set-up of the tower is presented in Figure 3. As shown in the figure, testing is expected to begin by early September. The anticipated test schedule is diagramed in Figure 4.

Figure 1. Insulation/Packer Simulation Test Tower

Figure 2. Section of Interior of Insulation/Packer Test Tower

Table IV. Data to be Monitored During Thermal Tests

	<u>IN</u>	<u>OUT</u>
Steam Mass Flow	X	
Steam Energy (heat)	X	
Steam Quality	X	
Steam Temperature	X	
Steam Pressure	X	X
Outer Tubing Temperature	X	X
Annulus Temperature	X	X
Casing Temperature	X	X
Cement Temperature	X	X
Soil Temperature	X	X
Pipe Temperature	X	X
Water Glycol Temperature	X	X

Figure 3. Test Facility Schedule

CY 1979

Figure 4. Test Schedule

CY 1979

	SEPT.					OCT.					NOV.				REMARKS
	35	36	37	38	39	40	41	42	43	44	45	46	47	48	
STEAMUP AND DEBUG	△	▽													
BARE TUBING STRING		△	▽												BOT PACKER
M.W. INSULATED STRING			△	▽											HALLIBURTON PACKER
C.S. INSULATED STRING				△	▽										GUIBERSON PACKER
THERMOCASE III STRING					△	▽									BAKER OIL TOOLS PACKER
BARE TUBING STRING							△	▽							NO PACKER, USE FLOW RESTRICTOR
SS INSULATED STRING									△	▽					SANDIA PACKER

ENHANCED RECOVERY PACKER

A. R. Hirasuna
L'Garde, Inc., Newport Beach, CA

The objectives of the first phase of the enhanced recovery packer program are to identify and characterize seal material candidates, and recommend most promising materials. The program is in its early stages, previous efforts having been concerned with geothermal requirements. The geothermal packer requirements are displayed in Figure 5. The effect of this environment on a selection of elastomeric materials is pictured in Figure 6. The progress toward improved hydrothermochemical stability of elastomers is contained in Figures 7 and 8. The results of simulation tests on elastomers are contained in Figures 9 and 10.

The requirements for the enhanced recovery packer are displayed in Figure 11. The packer concept used in the program is the L'Garde ERP Min-Stress II concept. Some aspects of the concept are given in Figure 12. The ERP program is summarized in Figure 13.

Figure 5. Geothermal Packer Requirements

- Develop packer seal elastomer compounds
- Geothermal environment
 - Temperature, 260°C (500°F)
 - Chemistry

H ₂ S	300 ppm
CO ₂	1,000 ppm
NaCl	25,000 ppm
H ₂ O	Balance
- Duty cycle, 24 hours

COMPANY B EPDM -- THIS AND L'GARDE EPDM REMAINED ELASTOMERIC AND SURVIVED FULL 24 HRS. ONLY DIFFERENCE L'GARDE EPDM EXTRUDED 2.5 INCHES VS COMPANY B'S 4.0 INCHES.

L'GARDE VITON -- FAILED BECAUSE OF INABILITY TO ELONGATE SUFFICIENTLY DURING SEATING.

COMPANY D EPOCHLOROHYDRIN -- LOST ALL STRUCTURAL STRENGTH AND BECAME SOFT, AND CRUMBLY BEFORE SEATING.

COMPANY E VITON -- FAILED BY BREAKING IN THE HIGH STRESS REGION. SURVIVED 3.75H WITH SLOW LEAK, THEN FAILED.

Figure 6. Post Test View of a Selection of Elastomeric Seals

Figure 7. Progress of Hydrothermochemical Stability of Geothermal Elastomers

Elastomer	Ult. Tensile @ RT		Ult. Elong. @ RT		Shore A Hard @ 260°C		Extrusion Resist. @ 260°C	
	Early	Present	Early	Present	Early	Present	Early	Present
EPDM Early-E263 Present-267	75%	97%	--	105%	85%	100%	57%	103%
Viton Early-115 Present-255	14%	72%	46%	101%	73%	100%	32%	55%
EPDM/Viton Early-235 Present-266	80%	96%	63%	84%	110%	101%	128%	96%
AFLAS Early-268 Present-291	77%	93%	112%	118%	90%	100%	84%	87%

Figure 8. Geothermal Elastomers Progress

Elastomer	Ult. Tensile @ RT. psi		Ult. Elong. @ RT %		Shore A Hard @ 260°C		Extrusion Resist @ 260°C, psia	
	V	CA	V	CA	V	CA	V	CA
EPDM Early-E263 Present-267	1363 1610	1020 1554	>840 141	>840 148	61 92	52 92	9.6 17.1	5.5 17.6
Viton Early-115 Present-255	1699 2195	244 1591	162 224	74 226	80 79	58 79	11.2 11.4	3.6 6.3
EPDM/Viton Early-235 Present-266	1882 1596	1506 1531	681 193	431 163	67 88	74 89	8.3 18	10.6 17.3
AFLAS Early-268 Present-291	1673 2335	1289 2162	394 134	442 158	69 95	63 95	6.7 17.4	5.6 15.2

PACKER SEAL SIM TEST EXTRUSION SUMMARY
CURRENT STATUS - OCTOBER 1978

ELASTOMER	500°F	400°F	300°F
EPDM	VERY MINOR	NONE	NONE
VITON	MODERATE	VERY MINOR	NONE
EPDM/VITON	NONE	NONE	NONE

Figure 9.

GEM O-RING SIM TESTS SYN. BRINE AT 260°C (500°F)

TYPE	COMPOUND	DIFFERENTIAL PRESSURE	2100 PSI	3100 PSI	4100 PSI	?
FLUOROELAST.	L'GARDE GEM VITON 255			22H	6.25H	
	PARKER FLUOROELAST. V-709-90		10.5H	9H	4H	
	PARKER FLUOROELAST. V-747-75		5.25H		0.2H	
EPDM	L'GARDE GEM NORDEL 267				22H	
	PARKER EPDM E-692-76				22H	
MISC.	L'GARDE GEM NORDEL/VITON BLEND 266				22H	
	L'GARDE GEM AFLAS 291				22H	
	DUPONT KALREZ 3074		22H	3.75H	0.75H	

Figure 10.

Figure 11. ERP Requirements

- Maximum Temperature, 371°C (700°F)
- Maximum Differential, 20.7 MPa (3000 psi)
- Steam/Water Environment
- 1 Year Maintenance Cycle

Figure 12. L'Garde ERP Min-Stress II Concept

- Patent Application in Process
- Adapts to Otis Packer
- Benefits from Knowledge Gained on Previous Efforts
- Relatively Simple and Inexpensive Because it is Adapted to a Production Packer

Figure 13. Enhanced Recovery Packer Program - Summary

- Developed Elastomer Compounds from 4 Polymer Systems Which Successfully Meets Unusually Severe Geothermal Environment
- Knowledge Gained on GEM Directly Applicable to Deep Steam ERP
- ERP Requirements Extremely Severe
- Phase I of Task 1 is Primarily Materials Identification, Characterization, and Selection of Seal Materials
- L'Garde ERP Min-Stress II Concept should be Practical Economic Solution to Deep Steam Requirements

HIGH PRESSURE COMBUSTION DOWNHOLE STEAM GENERATOR

K. M. Captain
Foster-Miller Associates, Waltham, MA

The system requirements for high pressure combustion downhole steam generation are presented in Figure 14. A packer which can withstand the DEEP STEAM conditions is under development. The packer utilizes an extruded metal seal (see Fig. 15) which is comparable with existing setting mechanisms as shown in Figure 16. A list of metals considered for the seal element is given in Figure 17. Aluminum has been chosen for the seal because it has a low extrusion pressure, good corrosion resistance, and adequate structural strength.

The high pressure combustor for the downhole generator is diagramed in Figure 18 and the prototype generator is shown in Figure 19. The combustor has been satisfactorily tested at atmospheric pressure. Results of the atmospheric test are listed in Figure 20. High pressure testing will be carried out at Sandia to determine operating characteristics, optimize geometry, study materials and heat transfer, and produce steam.

The surface facilities required for the high pressure combustion downhole generator are diagramed in Figure 21. Economic evaluation of recovery with the high pressure combustion generator indicates significant additional recovery within a relatively short period. A summary of the status of the program is displayed in Figure 22.

SYSTEM REQUIREMENTS

COMBUSTOR

- FIRING RATE — 20 MILLION BTU/HR
- STEAM FLOW — 16,000 LB/HR
- PRESSURE — UP TO 3000 PSI
- FUEL — NO. 2 FUEL OIL
- MINIMUM SOOT EMISSION

PACKER

- TEMPERATURE — UP TO 650°F
- FORCE — UP TO 100,000 LB
- SEAL ΔP — UP TO 3000 PSI
- RESISTANCE TO STEAM, EXHAUST GASES AND RESERVOIR FLUIDS

TUBE STRING AND SURFACE EQUIPMENT

- TUBE STRING LENGTH — UP TO 4500 FT
- SUPPLY AIR, WATER AND FUEL TO COMBUSTOR
- SUPPLY ACTUATION FLUID FOR PACKER DEPLOYMENT
- PROCESSING OF PRODUCED FLUIDS

Figure 14.

EXTRUDED METAL PACKER CONCEPT

SEAL MATERIAL REQUIREMENTS

- **LOW EXTRUSION PRESSURE**
- **HIGH CORROSION RESISTANCE**
- **LOW CREEP AT HIGH TEMPERATURE**

Figure 15.

HIGH TEMPERATURE PACKER ASSEMBLY

Figure 16.

EXTRUSION SEAL MATERIAL EVALUATION

MATERIAL	EXTRUSION PRESSURE (KPSI)	CORROSION RESISTANCE	CREEP STRENGTH
ALUMINUM 1100-0	9.9	RESISTS NEUTRAL AQUEOUS INORGANIC SALT SOLUTION — NEAR UPPER PORTION OF GALVNIC SERIES (ANODIC)	MEDIUM
COPPER (PURE)	25.2	GOOD RESISTANCE TO WEAK ACIDS AND BASES	MEDIUM
TITANIUM (PURE)	36.0	EXCELLENT RESISTANCE TO CHLORIDE SALT SOLUTIONS. RESISTS IMPINGEMENT, PITTING ATTACK	HIGH
SILVER (PURE)	41.0	RESISTS MOST DILUTE MINERAL ACIDS AND ALKALIS. ATTACKED RAPIDLY BY SULFUR- BEARING GASES	MEDIUM
INGOT IRON (ARMCO IRON)	42.0	POOR RESISTANCE IN MOIST ATMOSPHERE. VERY CLOSE TO STEELS ON GALVANIC SERIES (SLIGHTLY ANODIC)	HIGH
STEEL 1010	52.6	ATTACKED BY ACIDS. POOR RESISTANCE IN MOIST ATMOSPHERE	HIGH
NICKEL 200	57.6	GOOD CORROSION RESISTANCE TO STRONG ACID BASE SOLUTIONS	HIGH

CONCLUSION:

ALUMINUM HAS BEEN CHOSEN FOR THE EXTRUDED SEAL CONCEPT BECAUSE IT HAS A LOW EXTRUSION PRESSURE, GOOD CORROSION RESISTANCE, AND ADEQUATE STRUCTURAL STRENGTH

Figure 17.

HIGH PRESSURE TEST COMBUSTOR

Figure 18.

PROTOTYPE DOWNHOLE STEAM GENERATOR

Figure 19.

ATMOSPHERIC PRESSURE TEST RESULTS

- HIGH DEGREE OF FLAME STABILITY
- PERFORMANCE INDEPENDENT OF ATOMIZATION QUALITY
- EXHAUST GAS ANALYSIS INDICATES EFFICIENT COMBUSTION
($O_2 \approx \frac{1}{2} \%$, $CO_2 \approx 14.7\%$, $CO \approx 300$ PPM)
- NO DETECTABLE SOOT
- WIDE TURNDOWN RATIO (5:1)

Figure 20.

DEEP STEAM SURFACE FACILITIES FLOW DIAGRAM

Figure 21.

PROGRAM STATUS

COMBUSTOR

- **ATMOSPHERIC PRESSURE COMBUSTION TESTS COMPLETE, RESULTS SHOW COMBUSTOR HAS HIGH TURNDOWN RATIO WITH SOOT-FREE OPERATION**
- **HIGH PRESSURE COMBUSTOR TESTING STARTING AT SANDIA**

PACKER

- **FEASIBILITY OF EXTRUDING METAL SEAL ESTABLISHED**
- **SEALING CAPABILITY VERIFIED**
- **PROTOTYPE PACKER BEING ASSEMBLED**

ECONOMIC MODEL

- **RESERVOIR SIMULATION RESULTS SHOW SIGNIFICANT ADDITIONAL RECOVERY WITHIN RELATIVELY SHORT PERIOD**
- **COST MODEL BEING QUANTIFIED TO EVALUATE SYSTEM ON BASIS OF \$/BARREL OF OIL PRODUCED**

Figure 22.

LOW PRESSURE COMBUSTION DOWNHOLE STEAM GENERATOR

D. C. Wright, R. Binsley, L. Stabinsky
Rocketdyne Division, Rockwell International
Canoga Park, CA

The operating parameters and results of economic analysis for the low pressure combustion downhole steam generator are displayed in Figure 23. The downhole equipment is diagramed in Figure 24 with the combustion chamber presented in Figure 25. The combustion chamber is under testing, the test set-up is pictured in Figure 26. A close up of the combustor is given in Figure 27. The heat exchanger assembly is shown in Figure 28. The operating sequence for the generator is displayed in Figure 29. The heat exchanger section is an improved design, and a comparison with the original design is contained in Figure 30. Uphole equipment for the low pressure combustion downhole generator is diagramed in Figure 31. A summary of the effect of parametric variations on the cost of steam production with the low pressure combustion system is presented in Figure 32.

In addition to the development of a low pressure downhole steam generator, high pressure combustion experiments are being conducted to examine coking phenomena. The test conditions for the high pressure combustion are given in Figure 33. The test device is diagramed in Figure 34. The hardware listed is being designed and fabricated, and design details are being iterated.

Figure 23. Downhole Steam Generator Production Baseline Design

Operating Parameters

- 1500 psia, 85% quality, 1000 BBL/D steam
- 2500 ft
- 304 stainless vent and water pipes
- 11-3/4 in. casing, 7-5/8 in. vent pipe,
1-1/2 in water pipe
- 60°F air, fuel, water entering system
- 50% water flow through HX-3
- 0.34 lb/hp-hr SFC diesel engine
- 53% compressor efficiencies
- 45% pump efficiencies
- 90% effective uphole heat exchangers
- 737.2 lb/hr downhole fuel
182.9 lb/hr diesel engine fuel
- 15/1 air-to-fuel ratio downhole
35/1 air-to-fuel ratio in diesel engine

Economics

- \$1.73/BBL steam cost based on
 - \$129,621 annualized capital cost
 - \$501,935 annual operating cost
 - 10 year life
 - 10% discount rate
 - 6% inflation rate
 - \$15/BBL fuel cost

DOWNHOLE STEAM GENERATOR DOWNHOLE EQUIPMENT

Figure 24.

LOW PRESSURE COMBUSTION DOWNHOLE STEAM GENERATOR INSTALLATION 1000 BBL/DAY, 1500 PSIA., 85% QUALITY

Figure 25.

OVERALL VIEW OF IGNITION TEST SETUP

Figure 26.

COMBUSTOR IN IGNITION TEST SETUP

Figure 27.

HEAT EXCHANGER ASSEMBLY

Figure 28.

DOWNHOLE STEAM GENERATOR OPERATING SEQUENCE

TURN ON:

- WATER
- MAIN AIR
- PILOT NAT GAS
- CW AIR
- CW NAT GAS

Figure 29.

DOWNHOLE STEAM GENERATOR HEAT EXCHANGER DESIGN IMPROVEMENT

ORIGINAL CONCENTRIC TUBE APPROACH

- EXTERNAL PRESSURE ON LARGE DIAMETER TUBE
- THICK WALL
 - HEAVY WEIGHT
 - LIMITED THERMAL CYCLING
- HOT WALL - INCONEL 625
- LIMITED PRESSURE CAPABILITY
- LIMITED FLOW CAPACITY
- DIFFICULT ASSEMBLY
- EXPENSIVE

IMPROVED TUBE BUNDLE APPROACH

- INTERNAL PRESSURE ON SMALL DIAMETER TUBES
- THIN WALLS
 - LIGHTER WEIGHT
 - NO SERIOUS CYCLE LIMIT
- COOLER WALLS - INCOLOY 800
- NO SERIOUS PRESSURE OR FLOW LIMIT
- WELDING & BRAZING PROCESSES AVAILABLE
- SHORTER LENGTH

Figure 30.

DOWNHOLE STEAM GENERATORUPHOLE EQUIPMENT

Figure 31.

SUMMARY OF PARAMETRIC RESULTS

PARAMETER	RANGE	STEAM COSTS, \$/BBL	
		MINIMUM	MAXIMUM
● EXCESS AIR	0 - 15%	1.787 (0)	1.855 (15)
● FLOW SPLIT	25 - 60%	1.802 (55)	1.816 (25)
● INSULATION THICKNESS	0 - 1.2 INCHES	1.743 (0)	1.886 (1.2)
● UPHOLE HEAT EXCH. EFFECTIVENESS	80-97.5%	1.815 (92.5)	1.831 (80)
● STEAM QUALITY	80 - 100%	1.773 (80)	1.950 (100)
● STEAM FLOWRATE	500 - 1000 BBL/DAY	1.816 (1000)	2.219 (500)
● FUEL COST	15 - 30 \$/BBL	1.816 (15)	2.947 (30)
● DOWNHOLE HEAT EXCH. GAS EXIT TEMP.	800 - 1200 °F	1.805 (1200)	1.825 (800)
● VENT PIPE SIZE	4 - 7 INCH	1.759 (6)	1.862 (4)
● DIESEL SFC	0.34 - 0.425 LB/HP·HR	1.816 (0.34)	1.84 (0.425)
● WELL DEPTH	1000 - 5000 FT	1.758 (1000)	1.924 (5000)
● STEAM PRESSURE	1500 - 2500 PSIA	1.787 (2500)	1.816 (1500)
● SYSTEM LIFE	2.5 - 10 YRS	1.816 (10)	2.564 (2.5)

Figure 32.

HIGH PRESSURE DOWNHOLE STEAM GENERATION

TEST REQUIREMENTS

NOMINAL CHAMBER CONDITIONS

$$P_c = 1500 \text{ PSIA (NOM.)}$$

$$T_c = 3750\text{F}$$

	FLUIDS		
	FUEL	OXIDIZER	COOLANT
	#2 FUEL OIL	AIR	WATER
SUPPLY PRESSURE, PSIA	1525	1725	300
SUPPLY TEMPERATURE, °F	60F	110F	60F
FLOW RATE, LB/SEC	0.188	2.822	3.813

Figure 33.

HIGH PRESSURE DOWNHOLE STEAM GENERATOR

Figure 34.

PHYSICAL SIMULATION

D. A. Krueger
Sandia and Colorado State University

An outline of the Physical and Mathematical simulations programs is contained in Figure 35. The results of computer simulations using the Intercomp in situ combustion code for pure steam and steam with various combinations of combustion gases are graphed in Figure 36. The results demonstrated the desirable effects of carbon dioxide in the recovery process. A computer prediction for steam and steam with combustion gases for different reservoir conditions, carried out by Gulf Research, is graphed in Figure 37. A comparison of the computer predictions is displayed in Table 5 with reservoir characteristics given in Table 6. An examination of reasons for differences in the recovery between the two codes is displayed in Table 7. Laboratory experiments using a modified Hele-Shaw cell (glass bead contoured with the cell) were carried out to examine recovery behavior with various steam/gas combinations. The results are given in Figure 38 where freon was used as a surrogate gas for high pressure CO_2 . The laboratory experiments produced improved recovery with steam and simulated CO_2 .

Figure 35. Mathematical and Physical Simulations

- I. Properties of Kern River Crude
 - Core Laboratories
 - Anachem
 - Sandia Laboratories
- II. Computer Modeling
 - Intercomp
 - Gulf
 - Ecodynamics and New Mexico Petroleum Res. Ctr.
- III. Laboratory Modeling
 - Sandia Laboratories
 - Tejas Petroleum Engineers
- IV. Feasibility Study
 - Dynamics Technology, Inc. and Cal Tech.

FIGURE 36. PREDICTED RECOVERY FOR STEAM AND STEAM WITH COMBUSTION GAS, BASED ON GULF CODE.

FIGURE 37. PREDICTED RECOVERY FOR STEAM AND STEAM WITH
VARIOUS COMBUSTION GASES, BASED ON INTERCOMP CODE.

Table 5. Comparison of Results Predicted by Computer Simulation

	<u>Intercomp</u>	<u>Gulf</u>
Steam Injection		
Fractional Oil Recovery	57.7% in 2100 days	46.5% in 80 days
Steam Plus Combustion Gases		
Fractional Oil Recovery	55.3% in 1400 days	49.5% in 112 days
Steam Plus CO ₂		
Fractional Oil Recovery	52.7% in 1080 days	Not predicted

Table 6. Reservoir Model Characteristics

	<u>Intercomp</u>	<u>Gulf</u>
Geometry	2.5 acre 5-spot	2.5 acre 5-spot
Depth to Top of Formation	4200 ft	4650 ft
Original Formation Pressure	1400 psi	1750 psi
Original Oil Saturation	60% of pore volume	50%
Original Water Saturation	40% of pore volume	50%
Oil Gravity	10° API	10° API
Oil Viscosity	3300 cp at 140 F 80 cp at 300 F	360 cp at 143 F 20 cp at 260 F
Maximum Injection Pressure	2300 psi	2700 psi
Maximum Injection Rate (1/4 well)		
Steam Only	125 B/D	486 B/D
Steam and Combustion Gases		
Steam	82 B/D	287 B/D
CO ₂	190 lb/hr	888 lb/hr
N ₂	700 lb/hr	3278 lb/hr
Minimum BHP in Producer	125 psi	100 psi
Maximum Liquid Production Rate (1/4 well)	250 B/D	1000 B/D

Table 7. Primary Reasons for Gulf/Intercomp Difference

Avg. Injection Rate	Gulf	400 B/D
	Intercomp	75 B/D
Oil Mobility	Gulf	300 cp at 140 F
	Intercomp	3000 cp at 140 F
Avg. Porosity	Gulf	28%
	Intercomp	21%
Avg. Permeability	Gulf	1000 MD
	Intercomp	540 MD

Figure 38. Laboratory Recovery for Various Combinations of Steam and Gases

FIELD TESTING

R. L. Fox
Sandia Laboratories, Albuquerque, NM

The preparation for field testing of a high pressure combustion downhole steam generator has continued. The test location has been selected by Chevron, U.S.A. The location will be Chevron injection well 6-19 in Section 3 of the Kern River Field near Bakersfield, CA. The well is currently under steam with a well head pressure of approximately 320 psi. The current steam injection rate is approximately 300 barrels per day. The pressure and injection rate can be matched by the Sandia/Vapor Energy steam generator under testing at Sandia high-pressure facility. Construction permitting has been obtained from the Kern County Air Pollution Control Board. Legal arrangements between Sandia and Chevron, U.S.A. are in the final stages of negotiation. The complete generator and control system will be mounted on two portable skids for operation in the field. It is expected that field operation will be initiated during the last quarter of calendar year 1979.

SUMMARY OF PANEL DISCUSSION

- I. Injection String Modification Program
 - A. Shell Calcium Silicate insulation should be included in the test program.
 - B. Alternative methods to packers for reducing flow within the annulus need to be examined.
- II. Thermal Packer Development
 - A. Metal Packer
 - 1. Testing with thermal cycling, intentionally flawed casing, and operational temperatures effect on differential expansion, plus long term tests under temperature and corrosive environment.
 - 2. Consider age hardening alloys.
 - 3. Full scale laboratory evaluation and field testing should be pursued as soon as possible.
 - B. Minimum Stress Packer
 - 1. Consider testing environment carefully as some elastomers (which have looked good in geothermal) are especially susceptible to oil, oxygen, and combustion gases.
 - 2. Cycling important for test approach.
- III. Downhole Steam Generator
 - A. Quality of water required with new low pressure combustion design needs to be investigated.
 - B. An updated economic study of both high and low pressure systems needs to be carried out.
 - C. Reliability of downhole valves needs to be determined.
 - D. The running of multiple-string well completions needs to be demonstrated.
- IV. Field Testing
 - A. Materials coupons, for corrosion monitoring, should be an integral part of field test operations.
 - B. Completion Technology Co. is a good choice for production and well completion consultants.

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